Aalborg Universitet

Simple methodology to estimate the mean hourly and the daily profiles of domestic hot water demand from hourly total heating readings

Marszal, Anna Joanna; Zhang, Chen; Pomianowski, Michal Zbigniew; Heiselberg, Per Kvols; Gram-Hanssen, Kirsten; Hansen, Anders Rhiger

Published in:
Energy and Buildings

DOI (link to publication from Publisher):
10.1016/j.enbuild.2018.11.035

Creative Commons License
CC BY-NC-ND 4.0

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

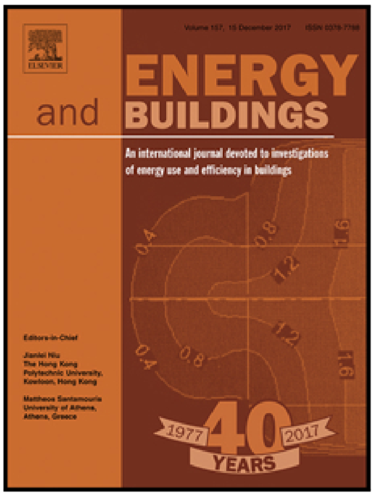
Citation for published version (APA):
Marszal, A. J., Zhang, C., Pomianowski, M. Z., Heiselberg, P. K., Gram-Hanssen, K., & Hansen, A. R. (2019). Simple methodology to estimate the mean hourly and the daily profiles of domestic hot water demand from hourly total heating readings. *Energy and Buildings*, *184*(2), 53-64. https://doi.org/10.1016/j.enbuild.2018.11.035

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy
If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Accepted Manuscript



Simple methodology to estimate the mean hourly and the daily profiles of domestic hot water demand from hourly total heating readings

Anna Marszal-Pomianowska , Chen Zhang , Michal Pomianowski , Per Heiselberg , Kirsten Gram-Hanssen , Anders Rhiger Hansen

PII: S0378-7788(18)32126-1
DOI: https://doi.org/10.1016/j.enbuild.2018.11.035
Reference: ENB 8911

To appear in: *Energy & Buildings*

Received date: 26 July 2018
Revised date: 14 November 2018
Accepted date: 19 November 2018

Please cite this article as: Anna Marszal-Pomianowska , Chen Zhang , Michal Pomianowski , Per Heiselberg , Kirsten Gram-Hanssen , Anders Rhiger Hansen , Simple methodology to estimate the mean hourly and the daily profiles of domestic hot water demand from hourly total heating readings, *Energy & Buildings* (2018), doi: https://doi.org/10.1016/j.enbuild.2018.11.035

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

ACCEPTED MANUSCRIPT

Highlights

- Energy use for DHW accounts from 16% up to 50% of total heat requirement
- Method to estimate mean hourly and daily profile of DHW from total heating readings
- Method gives good results when DHW share in total heating demand is minimum 50%
- Better understanding of users' practice related to DHW and space heating is crucial

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Simple methodology to estimate the mean hourly and the daily profiles of domestic hot water demand from hourly total heating readings.

Anna Marszal-Pomianowska[a]*, Chen Zhang[a], Michal Pomianowski[a], Per Heiselberg[a], Kirsten Gram-Hanssen[b], Anders Rhiger Hansen[b]

[a] Department of Civil Engineering, Aalborg University, Aalborg, Denmark
[b] Danish Building Research Institute, Aalborg University, Copenhagen, Denmark
*corresponding author: ajm@civil.aau.dk

Abstract:

During recent years, the research in reduction of energy use in buildings has focused primarily on decrease of space heating needs, energy for ventilation and recently cooling, whereas domestic hot water (DHW) has been overlooked. In 2013, the energy use for DHW was estimated at 16% of total heat requirement in EU28 households, but in new energy-efficient buildings this share is documented to be around 40-50%. Generally, however, there is limited knowledge of DHW. This paper presents a simple methodology, which enables calculation of the mean hourly and the daily profiles of DHW demand from hourly values of the building total heat demand, and thus contributes to gaining a better understanding of the DHW usage. The method is validated with data from single-family houses and apartments and afterwards applied to dataset consisting of hourly total heat consumption readings from 38 single-family houses delivered by district heating. The method gives satisfying results when the DHW usage during summer is at least at the same level as the space heating demand, which is the case in apartments and in the energy-efficient houses. The standard deviation was used as preliminary classification criterion for deciding if the method can or cannot be applied. Two limits were found $\sigma > 240$ for apartments and $\sigma < 800$ for single-family houses.

Keywords: Domestic hot water; load profiles; calculation method; hourly DHW usage;

Nomenclature

Symbol	Definition	Unit
i	Time step	h
q_{cal}	Hourly DHW usage	Wh
$\overline{q_{cal}}$	Calculated mean hourly DHW usage	Wh
$\overline{q_{meas}}$	Measured mean hourly DHW usage	Wh
q_{tot}	Hourly total heat demand	Wh
$q_{tot\ min}$	Minimum total heat demand during summer day	h

$q_{tot\ night}$	Mean total heat demand during between 0:00-4:00 a.m.	h
t	Period of analysis	-
δ	Relative error	(%)
σ	Standard deviation	-

1. Introduction

As stated by the European Commission, heating and hot water in EU households account for 79 % of total energy use in buildings [1]. At the same time, present knowledge and understanding of energy use for domestic hot water (DHW) and its production seem to be insufficient. During recent years, the research in reduction of energy use in buildings, in European countries, has focused primarily on reduction of space heating needs, energy for ventilation and recently cooling. One of the reasons for the insufficient attention towards energy use for DHW is that, in many cases, heating energy use has been considered as the total heat use for space heating and domestic hot water combined. Measures to reduce energy use were focused on space heating use, and DHW was overlooked. A supporting fact to this statement is that in 2007 the Danish Energy Agency issued 10 measures to save energy [2] and none of them considered DHW. Until presently, there has not been much improvement for DHW energy use, and this situation has stayed unchanged for many years, causing an increased relative share of DHW in the overall energy use in the buildings, see example of Danish building regulations depicted in Figure 1.

As reported in [2], in Denmark in years 1989 to 2009 the DHW consumption per capita has increased approx. from 10 m^3/year to 15 m^3/year while total domestic water (hot and cold) has dropped from approx. 70 m^3/year to approx. 45 m^3/year. It is indicated that the increase of DHW is due to elevated user consumption but as well large loss related to DHW circulation and higher comfort expectations. In 2013, the energy use for DHW was estimated at 16% of total heat requirement in EU28 households [3],

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

but in new energy-efficient buildings this share is documented around 40-50% [4]. As indicated in [5–7], estimated energy use for DHW is between 20% and 30% of the total energy use of the residential buildings. Undoubtedly, this is a significant share, and the fact that research publications indicate this number as an estimate is an alarming issue itself.

Moreover, energy efficiency of energy systems is dependent on DHW consumption profiles and therefore better understanding of DHW consumption habits is required. As indicated by [8], dimensioning and operation of, for example, solar assisted energy systems with heat storage is highly dependent on outdoor transient daily condition and transient daily DHW consumption profiles. Also in [9] it was highlighted that realistic energy use profiles are required for optimization of design and operation of energy systems.

As indicated in the publication of the International Energy Agency activity Annex 42 [10], the DHW use pattern in residential buildings is similar but still quite diverse in different countries. Samplings with frequencies between 1.5-min to 1-hour in 8 countries have indicated morning and evening peaks, but their magnitude and width were significantly different, which was explained by different weather conditions, cultural habits and occupants' presence. However, the largest sample size used in the analysis was 12 households and cannot be considered as representative sample size, since such little sample size can lead to faulty conclusions. Furthermore, another study within a single country has shown that different types of households have great variation of daily peaks, i.e. some have a marked morning peak, others have a marked evening peak, and a third group have more leveled distribution during the day [11].

ACCEPTED MANUSCRIPT

Not only DHW pattern is reported diverse but also DHW consumption per person is reported different from country to country. As indicated by [12], DHW consumption in average is typically 30 - 70 l/day per person . However, the reported spread is much larger, e.g. for Turkey 45 l/day per person at 60 ºC [13], for Canada 79 l/day per person [14], for USA between 56.8 and 75.8 l/day per person [15] or even between 119 and 283.5 l/day per person [16].

The DHW consumption has been also investigated and related to multiple other parameters. In [17] energy for preparation of DHW was obtained from 1993 SHEU dataset for the Canadian housing stock. The DHW models were obtained only for households with electrical DHW heating system by deducting electricity use for appliances, lighting, space cooling from the total electrical bill. The possible high error of the method is pointed even by the authors of the study, but still due to the lack of disaggregated data for DHW electricity consumption, it was decided to follow the approach. In [18] large sample of 204 residences in Central Florida has been monitored with respect to electricity use for DHW production. Authors have linked energy use with number of occupants per household. The data showed, as expected, that the more occupants the higher energy use for DHW production per household and that occupancy has the strongest influence on energy use for DHW. The monitoring campaign has as well shown that the more occupants per household, the lower energy use per occupant for DHW preparation. Study revealed as well that weekday water heating energy use is similar, except Friday with significantly lower energy use. Weekend days show higher hot water energy consumption and peaks at later time comparing to weekdays.

ACCEPTED MANUSCRIPT

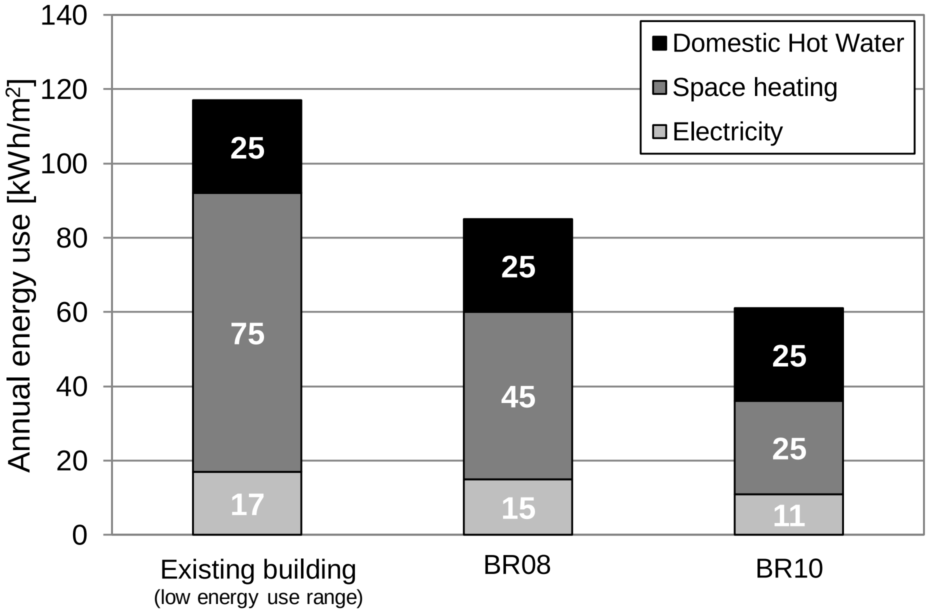


Figure 1 Distribution of annual energy use for hot water, space heating and electricity in existing building and in new house building according to Danish building regulations (BR) 2008 and 2010 [2]

Detailed load profiles for domestic energy use are important as input to simulation models to predict energy use in buildings. High resolution measuring campaigns could be the source for such data [3]. Yet, due to high cost and resource demands (e.g. measuring equipment, user approval) and long measurements timeframe, these measuring campaigns are seldom performed. In Denmark, 63 % of citizens are connected to district heating (DH) [19], and presently more and more Danish households are equipped with smart meters that not only measure seasonal energy use, but also dynamic energy demand. For example, recently the second largest Danish district heating AffaldVarme Aarhus has changed two-thirds of the household meters (56 000 units) to new smart meters. These meters enable collecting high frequency data (with 1-hour and even lower time steps) on building total heat demand. As indicated in [20], most research so far provides information on daily or annual average DHW use that is of limited use. The access to high resolution data from district heating smart meters might be the key to gain a better understanding of DHW demand. However, the metered data from DH suppliers only indicate the total heat demand of a building , without the division between space heating and DHW.

Therefore, the objective of this paper is to present a simple methodology, which enables calculation of the mean hourly and the daily profiles of DHW demand from hourly values of the building total heat demand, and thus contributes to gaining a better understanding of the DHW usage. Furthermore, this method visualizes the significant knowledge and information potential of smart metering data.

The paper is structured as follows. Section 2 describes the developed methodology. Section 3 gives an overview of the material used for methodology validation. Section 4 presents the results of the validation and section 5 demonstrates how the method can be applied in practice. The paper is finalized with a discussion section and the concluding chapter.

2. Methodology

This section introduces the methodology used to estimate the hourly energy demand and the daily consumption profile for DHW usage with only hourly values of total heat demand. The proposed methodology builds on an assumption that outside of the heating season and in particular during the three warmest months in Denmark, i.e. June, July and August cf. *Figure 2*, the space heating demand is constant and independent of the room temperature and the heat demand is predominantly associated with use of domestic hot water, cf. Figure 3

ACCEPTED MANUSCRIPT

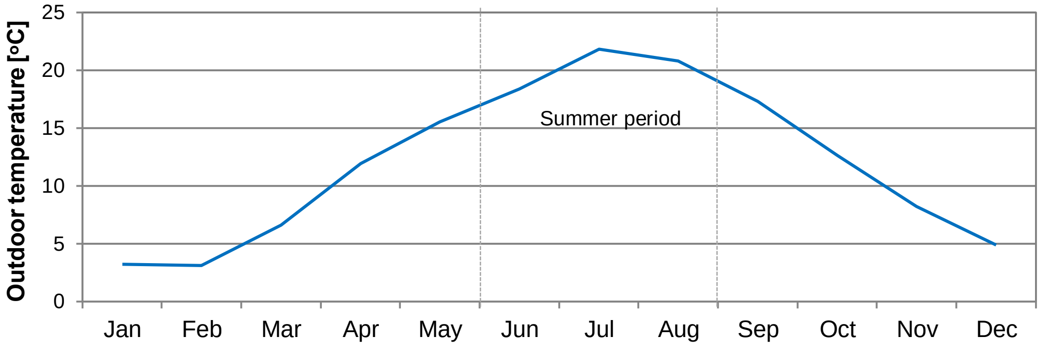


Figure 2. Monthly mean outdoor temperature in Denmark [source Danish Meteorological Institute]

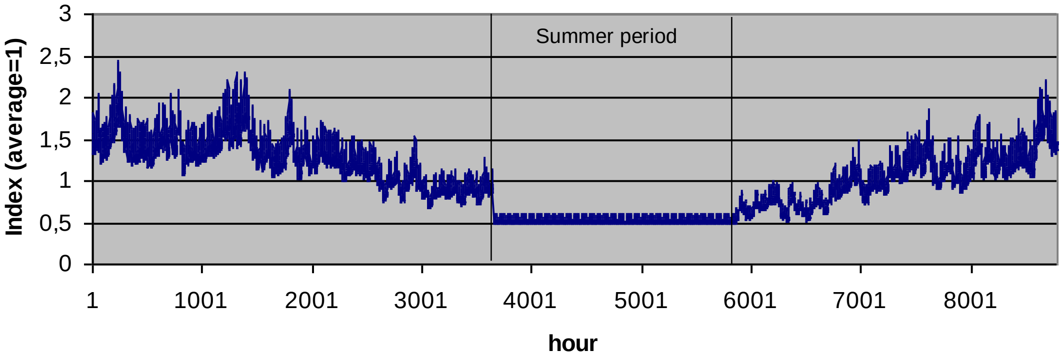


Figure 3. Hourly distribution of the total heat demand of a typical house in Denmark

Furthermore, according to the EU statistics people spend daily around 17 hours at home daily (for people aged over 65, it increases to around 20 hours and for the youngest group, aged between 15-24, it decreases to around 14 hours) [21]. Consequently, there should be a time of the day where the hot water consumption is zero due to the occupants' absence at home. Another time of the day, when the hot water use should be zero is when occupants sleep. Between 0:00-04:00 more than 80 % of Danes and more than 90% of Europeans sleep [21,22]. The facts about the daily rhythm of people were used to exclude the heat demand unrelated to the hot water use from the daily profiles. Figure 4 outlines the calculation procedure and graphically shows particular steps of the method, which are as follows:

$t \in (1st\ of\ July - 31st\ of\ August)$ (1)

$q_{tot}\,(i) = \frac{1}{t}\sum_{i=0}^{t} q_{tot}\left((i*24)+1\right), \quad i \in (1;24)$ (2)

$Method1\colon \quad q_{tot\ min} = \min\left(q_{tot}\,(i)\right)\ (3a) \qquad and \qquad Method2\colon \quad q_{tot\ night} = \frac{1}{4}\sum_{i=0}^{4} q_{tot}(i)$ (3b)

$Method1\colon \quad q_{cal}\,(i) = q_{tot}(i) - q_{tot_{min}}\ (4a)\ \ and \qquad Method2\colon \quad q_{cal}(i) = q_{tot}(i) - q_{tot_{night}}$ (4b)

5. $\overline{q_{cal}} = \frac{1}{24}\sum_{i=1}^{24} q_{cal}(i)$ (5)

Firstly, the three summer months are selected. Secondly, the daily heat demand profile for an average summer day is calculated. In the third step, separately for each assumption (Method 1 – when people are not at home, the hot water use is zero, Method 2 – when people are at sleep, the hot water use equals zero), the consumption that is not related to how water use is identified. In the fourth step, the no-DHW consumption is deducted from the value at each hour of the day. In the final step, the average daily profile of how water use is obtained, and the average hourly hot water demand are calculated.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

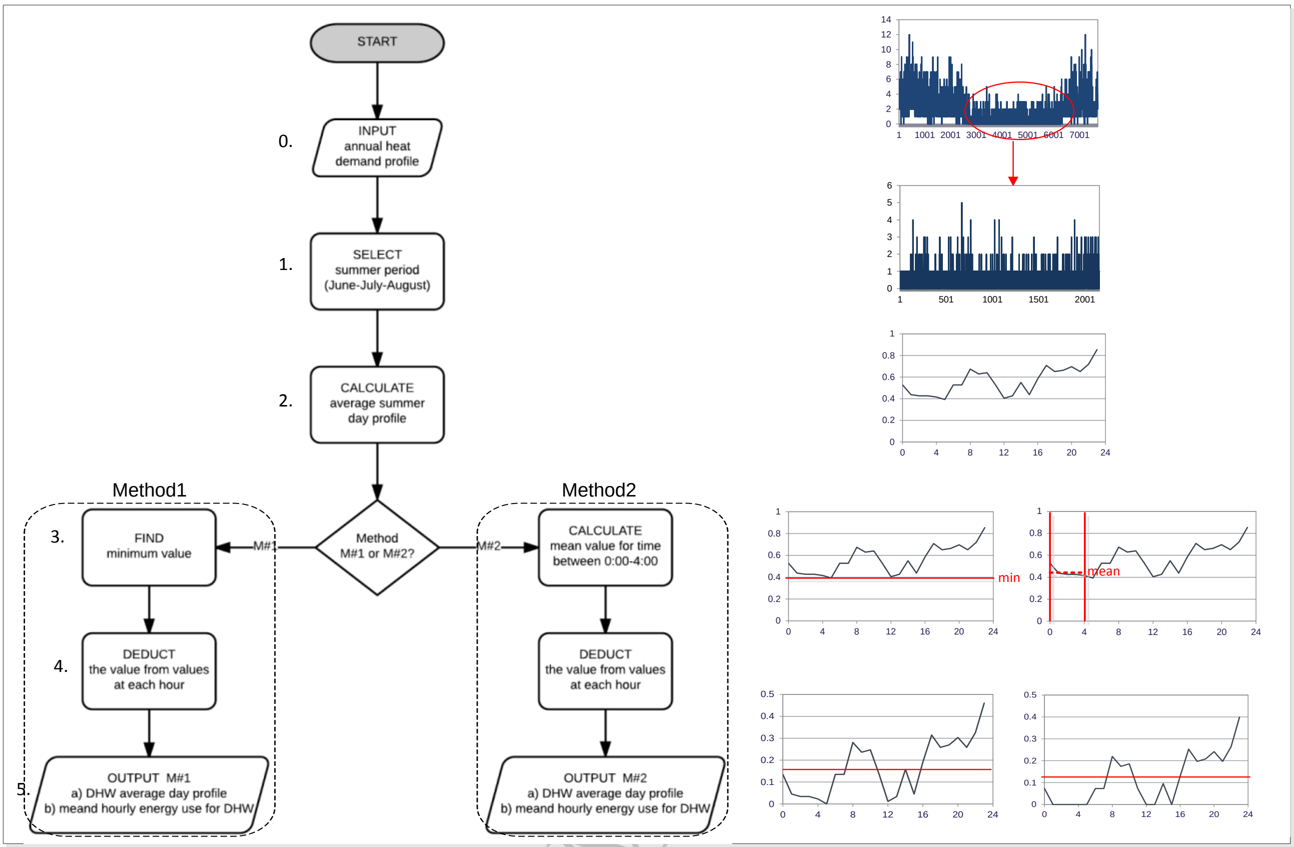


Figure 4: Flow chart of the methodology

3. Material

The methodology is validated with four datasets described in Table 1. The VAL-APP-2016 dataset is comprised of separated DHW and space heating measurement data for 28 apartments. The measurement data for space heating includes water flowrate and supply and return temperatures, while the data for DHW only contains water flowrate. In order to calculate the energy consumption for DHW, the supply and return temperatures are assumed to be 55^{o}C and 10^{o}C, respectively. These apartments were originally built in the 1970s and newly renovated in 2015. Information on the number of occupants in the apartments is not available, but the floor area for these apartments range from 67.2 m^2 to 111.7 m^2. Radiators are used as emitters for space heating in all the apartments.

ACCEPTED MANUSCRIPT

The measurements of space heating and DHW from 50 single-family houses of different age form the VAL-HOU-2012(4) data set. In all houses the heat source for space heating and DHW is the heat pump equipped with domestic hot water tank. Beside from the energy measurements, there is also the additional data on building, i.e. age, floor area, type of construction and type of emitters (radiators or underfloor heating), and the data on household, i.e. the number of occupants and their age (they are divided into three age groups: kids, teenager, adult). The measurements were part of the StyrdinVarmePumpe project [23].

The VAL-HOU-2010(1) data set is also comprised of measurements from single-family houses. The five new built houses are constructed as passive houses and all are equipped with heat pumps and domestic hot water tanks. The three renovated houses are connected to district heating network, which delivers heat for space heating as well as DHW. Similar to VAL-HOU-2012(4), the information on households and building characteristics is available. The measurements were conducted as part of the Comfort Houses project [24].

The data set - VAL-HOU-2010UK - used for model validation consists of measurement conducted in the United Kingdom in 10 single-family houses. The data encompasses measurements of total heat demand and space heating. The DHW consumption was not directly measured but it was calculated as the difference between the total and the space heating demand. No other information on buildings, e.g. the area, the year of construction, the location and households, e.g. the number of occupants, age, gender, is available.

The DH-AVA-2013 data-set is used to visualize the application of the methodologies. The data-set was delivered by the district heating supplier and includes hourly data from 38 single-family houses.

ACCEPTED MANUSCRIPT

Together with the heat consumption, the year of construction for each house is known. Unfortunately, no other information on buildings and occupants is available.

Table 1. Overview of data-sets used in the analysis.

Data-set	Description	Time period covered	Geographical location	Type and number of houses	Data resolution
VAL-APT-2016	Measurements of both domestic hot water and space heating usage for each apartment	Continuously between Jun to Aug 2016	Aalborg, Denmark	28 apartments	Hourly data
VAL-HOU-2012(4)	Separate measurements of domestic hot water and space heating	Jan-Dec. 2012 or Jan-Dec. 2014	Not stated explicitly where in Denmark	50 single-family houses of different age	Hourly data
VAL-HOU-2010(1)	Separate measurements of domestic hot water and space heating	Jan-Dec. 2010 or Jan-Dec. 2011	Vejle and Aarhus area, Denmark	9 houses, of which 3 after renovation and 6 new built	Hourly data
VAL-HOU-2010UK	Separate measurements of total heat demand and space heating	Continuously from Jun to Aug 2014	Not stated explicitly where in the UK	10 single-family houses	10-minute data
DH-AVA-2013	Monitored data of total heat demand	Continuously from Sep 2013 to Sep 2014	Aarhus area, Denmark	38 single-family houses	Hourly data

4. Validation

This section presents the validation of the methodologies. It includes a verification of how well the mean hourly usage and hourly profile of DHW during a summer day are predicted compared to the measured values.

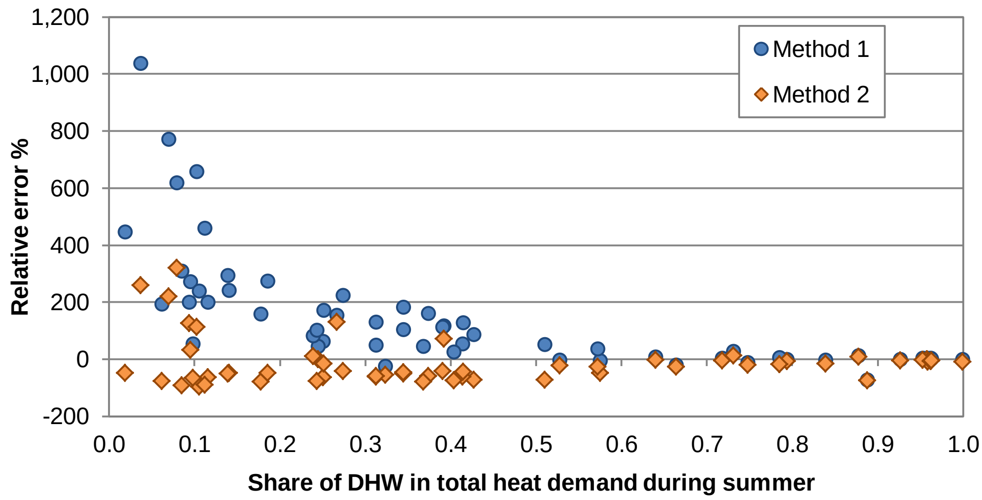
4.1 Mean hourly DHW usage

The relative error of mean hourly DHW usage is used to evaluate the accuracy of the methods, which is calculated by Eq (1). According to the literature, a reasonable prediction of hourly DHW usage is with the relative error of ±10% [25]. The positive relative error indicates that the method overestimates the

ACCEPTED MANUSCRIPT

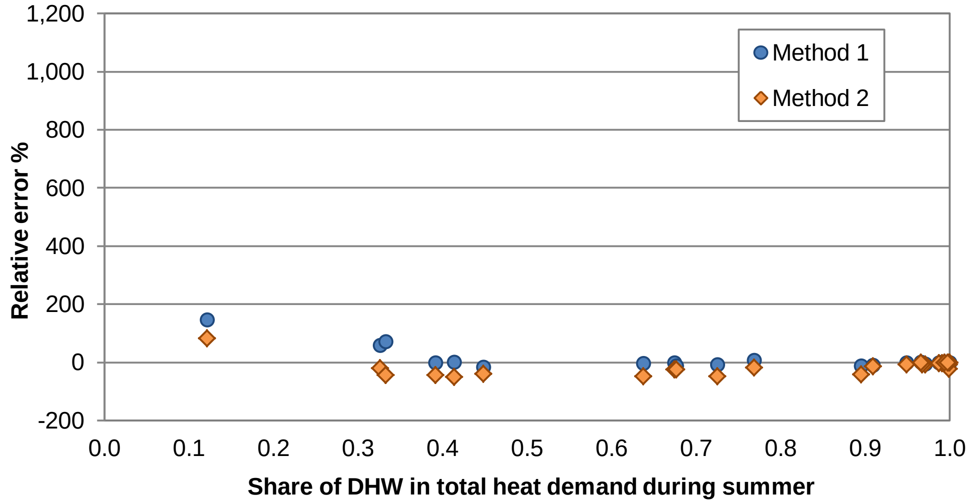
mean hourly DHW usage, while the negative one indicates underestimation. As indicated in Figure 5, there is a clear correlation between the accuracy of the methods and the ratio of DHW usage to the total heating demand. The relative error logarithmically decreases with the increase of the DHW usage ratio. Both methods could accurately predict the mean hourly DHW usage when the ratio is above 0.5. Method 1 tends to over-predict the mean hourly DHW usage whereas Method 2 has risks of both underestimation and overestimation when the ratio is below 0.5. However, the range of relative error is much narrower for Method 2 compared to Method 1.

$$\delta = \frac{\overline{q_{cal}} - \overline{q_{meas}}}{\overline{q_{meas}}} \times 100\% \qquad (1)$$



(a)

ACCEPTED MANUSCRIPT



(b)

Figure 5. The relative error of mean hourly DHW usage as a function of DHW share in total heating demand during summer (a) Single-family houses (b) Apartments

For further analysis, the accuracy of the methods and their influencing factors, the datasets are divided into different categories based on the building, system and occupant related factors. The accuracy of the methods is represented by the mean relative error with standard deviation, as shown in Figure 6.

Figure 6(a) illustrates the correlation between the accuracy of the methods and dwelling types. The dwellings from the validation datasets can be divided into two types: apartments and single-family houses. Both methods are able to provide more accurate results for apartments than the single-family houses. The mean relative errors for Method 1 and Method 2 are 7% and -14% for apartments, and 126% and -22% for single-family houses, respectively. The standard derivations on the relative error are ±32% and ±26% for apartments, and ±202% and ±80% for single-family houses, respectively. The high deviation on single-family houses could be explained by the fact that occupants in apartments are more likely to turn off the heating systems during summer, compared with those living in houses [26]. Therefore, the accuracies of the methods are high for apartments due to the high DHW usage ratio. The results also indicate that Method 1 tends to overestimate the DHW usage, whereas Method 2 tends to underestimate that.

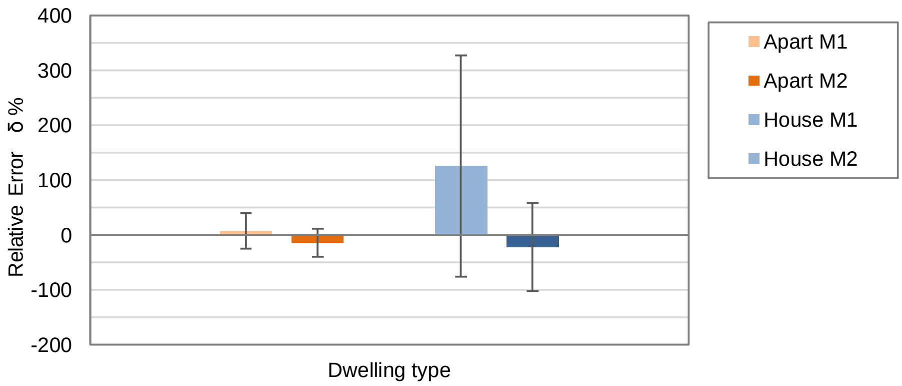
Another building related factor is the year of construction, as shown in Figure 6(b). Based on the TABULA concept [27], the residential buildings can be divided into typical age categories which reflect changes in building characteristic and changes in building energy requirements. In the VAL-APT-2016 dataset, all the apartments are constructed and renovated in the same period, so only single-family houses are classified and analyzed here. For Method 1, there is a clear tendency that the newer the buildings the smaller the deviation. For Method 2, the tendency is not obvious. The highest error exists for the houses built between 1999 and 2006, which is – 44%; while the lowest error exists for the houses built between 1931 and 1960, which is – 7%.

The type of heating emitter is also considered as a parameter that might influence the DHW usage. The single-family houses are equipped with four types of heating emitter: floor heating (FH), air/floor heating (A/FH), radiator (R) and radiator/floor heating (R/FH). Due to the limited number of cases with the air/floor heating and radiator/floor heating, it is difficult to draw any meaningful conclusions on this type of emitters. Therefore, the heating emitters are excluded from further analysis. However, it is possibly to identify that the relative error on mean hourly DHW usage doubles in the cases with radiators than the one with floor heating. Even though Method 2 has a lower mean relative error on radiator cases, the standard derivation range is much larger than the floor heating cases. This could be also explained by the fact that floor heating is not regulated as often as radiators, and that occupants do not turn it off during summer time since it creates discomfort due to cold floor, in particular tiles [28,29].

ACCEPTED MANUSCRIPT

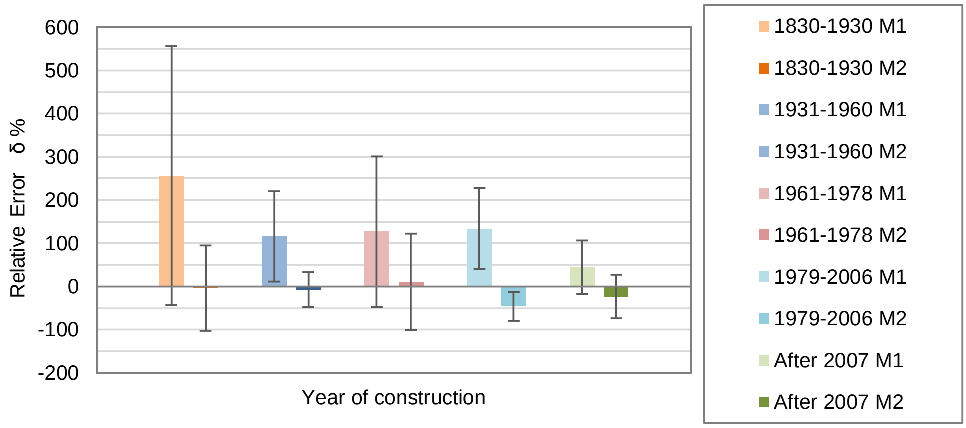
ACCEPTED MANUSCRIPT

Finally, the correlation between the accuracy of the methods and household size is investigated. Method 1 does not provide an accurate prediction of the DHW usage with small occupant size (1 or 2 people). This is because the share of DHW usage in the total heating demand is low when the houses are with a small group of occupants. With more occupants in the house, the relative error of Method 1 is significantly lower. Yet, Method 1 relies on the same usage pattern every day; however, with more people in the household the same pattern every day may be less likely, and hence resulting in that the error increases. The average relative error decreases to 5% when the number of occupants is 6. However, there are only four houses with such high number of occupants, and the results cannot be seen as representative. Method 2 assigns the night time, in particular hours between 0:00-4:00 a.m., as the period with no use of hot water and as most often all people are asleep at the same time, the accuracy of Method 2 is better than of Method 1. However, there is no strong relation between the relative error and the household size, as indicated in Figure 6.

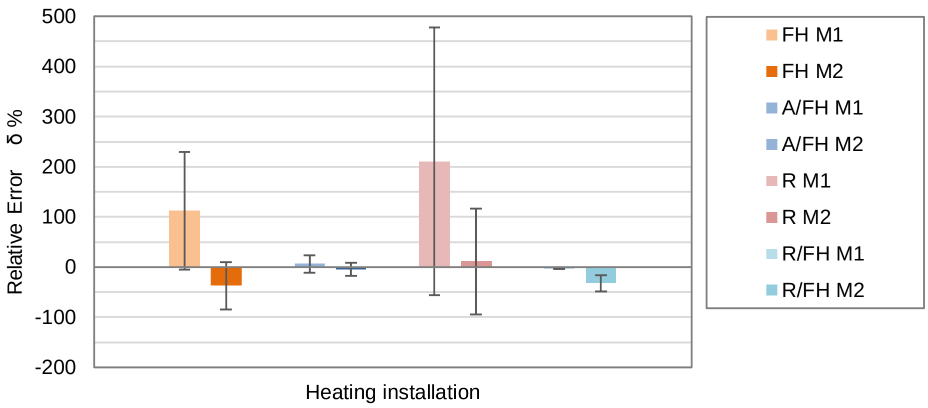


(a)

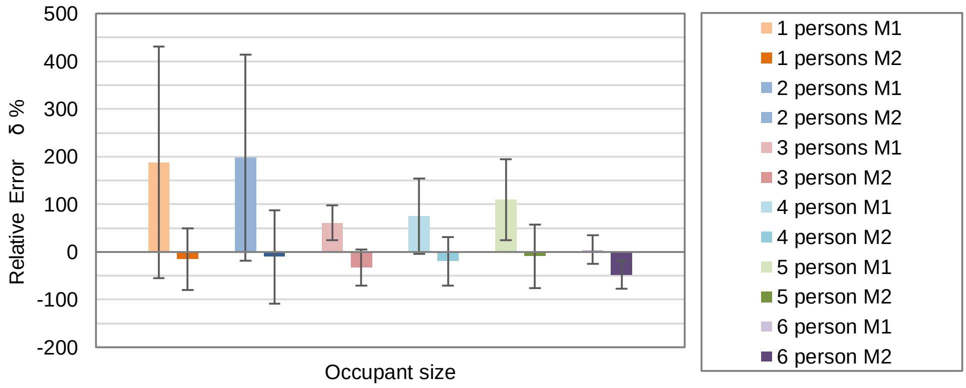
ACCEPTED MANUSCRIPT



(b)



(c)

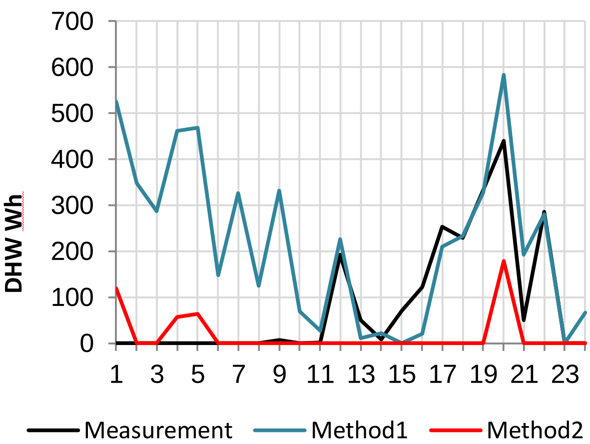


(d)

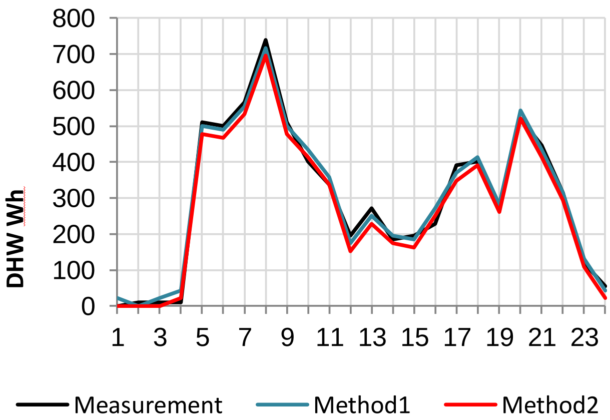
Figure 6. The modelled mean relative error with standard deviation and influencing factors (a) Dwelling type; (b) Year of construction; (c) Space heating installation; (d) Occupant number

4.2 Summer daily profile

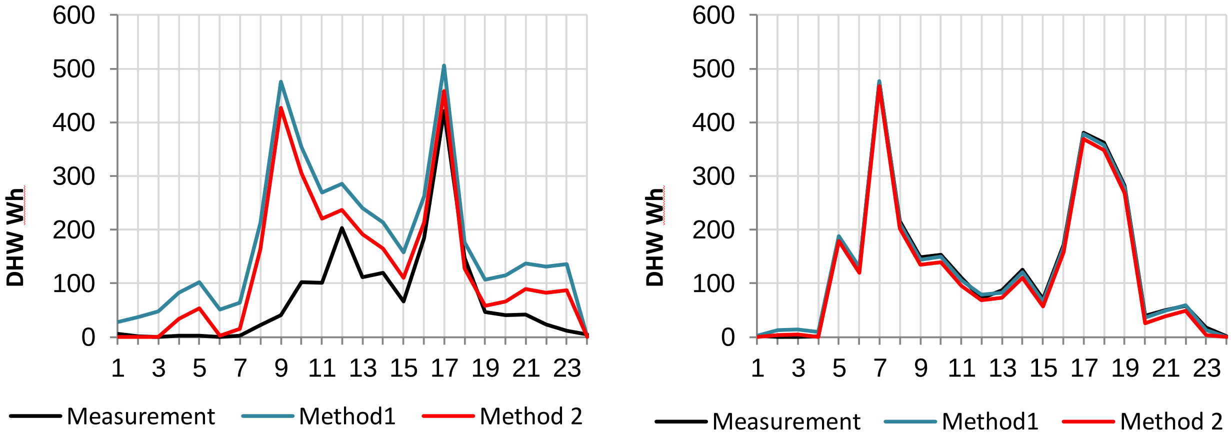
Figure 7 illustrates the modelled summer daily profiles of DHW usage compared to measured profiles in both single-family houses and apartments. Figure 7(a) and (b) demonstrate the profiles for single-family houses (VAL-HOU-2012(4)) with DHW usage ratio of 0.18 and 0.80, respectively. While, Figure 7 (c) and (d) demonstrate the profiles for apartments (VAL-APT-2016) with DHW ratio of 0.12 and 0.90, respectively. For the cases with high DHW usage ratio, the modelled profiles correspond well to the measured ones. However, both models fail to generate accurate profiles when the DHW ratio is low and space heating become the dominant heating demand. It is clear to see that there are two peak DHW usage periods during a day in both apartment and single-family house: one is in the morning and the other is in the evening. However, the peak hour and duration might be different based on occupant behaviour. Both models seem to be able to predict the peak pattern, but the models do not exactly capture the peak hour and magnitudes when the DHW ratio is low.



(a)



(b)

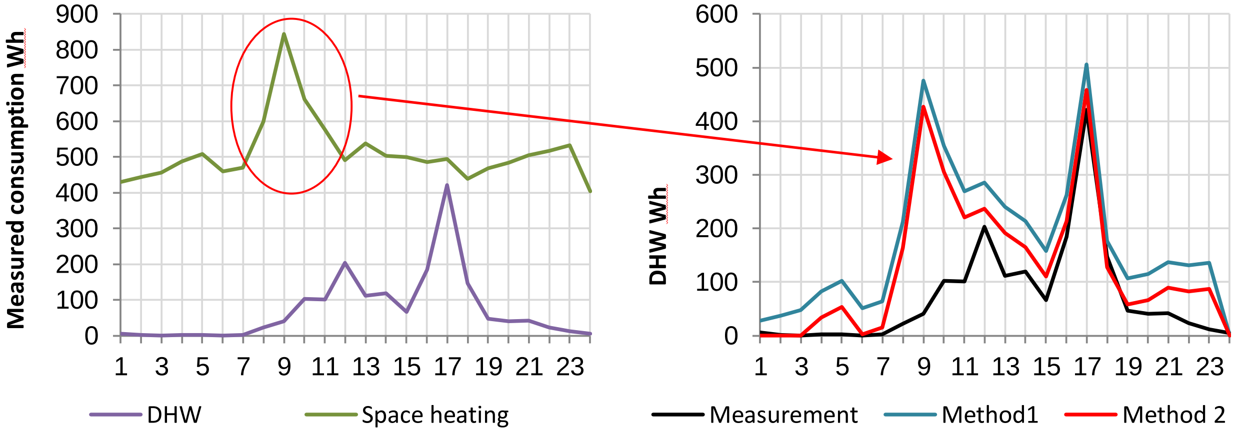


(c) (d)

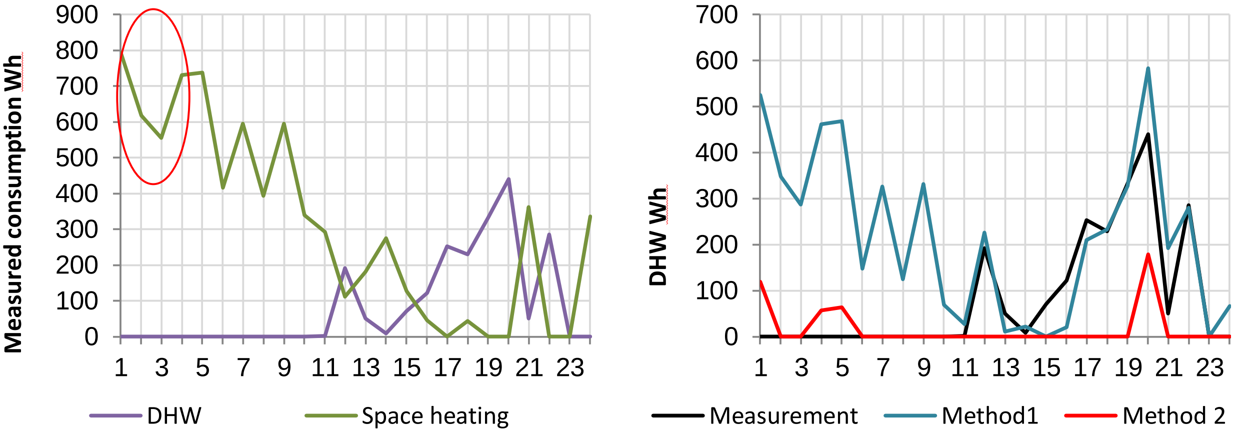
Figure 7. Mean daily profile of DHW (a) Single-family house, DHW ratio=0.18; (b) Single-family house, DHW ratio=0.8; (c) Apartment, DHW ratio=0.12; (d) Apartment, DHW ratio=0.9

Beside the DHW usage ratio, the accuracy of predicted DHW daily profile is strongly related to the daily usage pattern of space heating. As indicated in Figure 8 (a), there is a peak in space heating demand from 7 am to 11 am based on the measurement data, while the DHW demand is insignificant during this period. However, because both methods treat the space heating demand as a constant value during the entire day, the morning peak in the heating consumption will be considered as the contribution of DHW and overestimations on the DHW peak load occurs by using both methods. Another deviation occurs when the space heating demand is higher during the night (between 0 am and 4 am) than the rest of the day, cf. Figure 8 (b). Method 1 over-predicts the DHW usage during the night, whereas, Method 2 has a risk of underestimating the DHW usage in this case because it regards the space heating demand as a mean value during the night. Therefore, large deviations on the DHW daily profile prediction will appear in the cases where space heating usage varies significantly during the day.

ACCEPTED MANUSCRIPT



(a)



(b)

Figure 8. Measured consumption correlation to the methods' deviations (a) Deviation due to space heating peak load (b) Deviation due to high space heating demand during the night (0 am to 4 am)

5. Application of the methodologies

The two methodologies were used to calculate the hourly DHW demand from the monitoring data on heat consumption delivered by the district heating supplier. The DH-AVA-2013 data-set consists of hourly heat consumption data from 38 single-family houses of various size and age, cf. Figure 9. Beside the year of construction and floor area, no other details on the household such as number of occupants, their age and/or gender are known. For the buildings included in the DH-AVA-2013 data-set, there is a clear correlation between the heat demand and the size of the building, though the expected heat demand increase for older buildings is not as significant as described in [30].

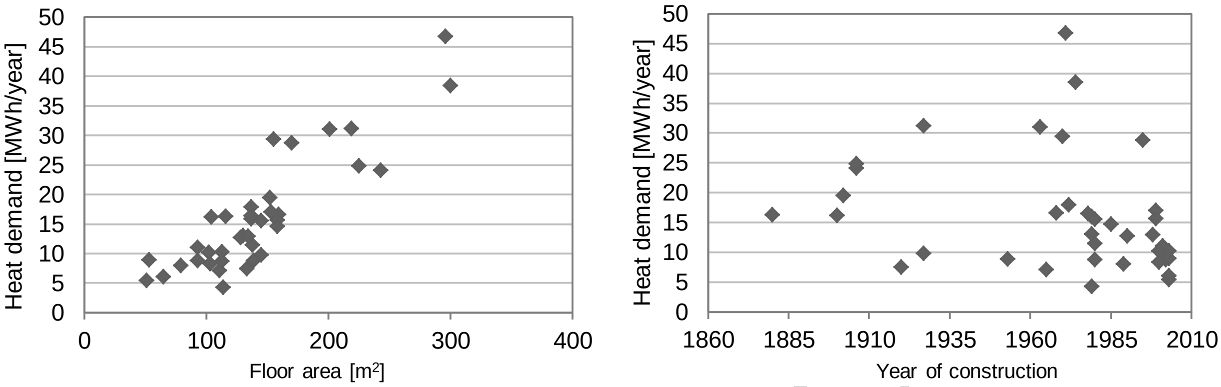


Figure 9. Annual heat demand in relation to the building floor area (left) and age (right).

5.1 The hourly DHW use

Figure 10 and Figure 11 depict the results of the first attempt to use the proposed methodologies to estimate the hourly DHW demand. For all 38 houses, Method 1 gives higher values of hourly DHW demand than Method 2. The difference ranges between 4%-85% (in relation to Method 1 values). These discrepancies are also visible in the daily DHW profiles of the selected four houses.

With the diminutive difference between Method 1 and Method 2, the daily profiles almost overlap each other, and the curves resemble possible DHW consumption profiles. For instance in case of house #1 there is a clear morning “hygienic” and evening “cooking/dishwashing” peak which may be typical for office working occupants with kindergarten/school kids. In case of house #26, there are also two peaks, but the time shift and longer duration of the morning peak could be more typical for occupants working from home or having more flexible working hours. With the big difference between the results of Method 1 and Method 2 as seen in house #3 and #20, the curves do not resemble any of the typical

DHW demand profiles. Here, the DHW consumption peaks during night hours, which is when we expect occupants to be asleep and not perform any DHW-related activities.

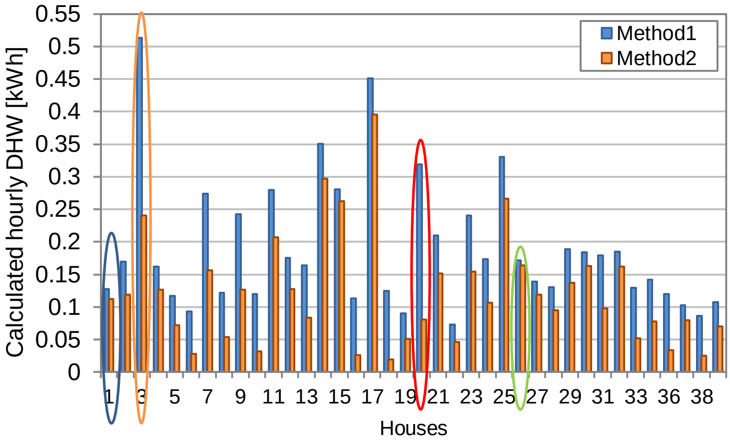


Figure 10. Calculated mean hourly DHW consumption for the 38 houses

The input data, i.e. the heat demand profiles shown in Figure 12 show that for the houses where the daily heat demand varies significantly during the summer period (house#3 and #20), the output DHW profiles and hourly demand are questionable. The input profiles indicate that during some days, heat is not only used for the domestic hot water but also for other purposes, which do not have a regular pattern and constant consumption but rather happen occasionally, e.g. due to sudden decrease of outdoor temperature and/or activation of floor heating in bathroom or kitchen Thereby, for such houses, the summer period is not representative for heat consumption related solely to DHW.

ACCEPTED MANUSCRIPT

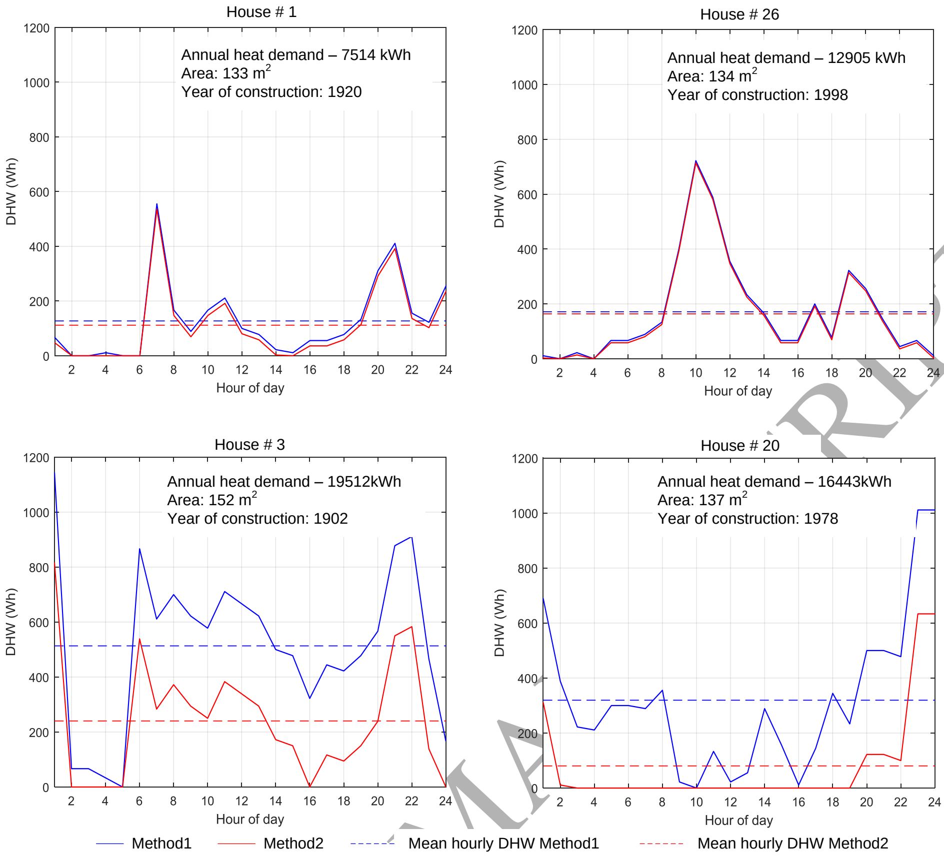


Figure 11. Examples of daily DHW profiles for cases with good match (top) and mismatch (bottom) between Method 1 and Method 2.

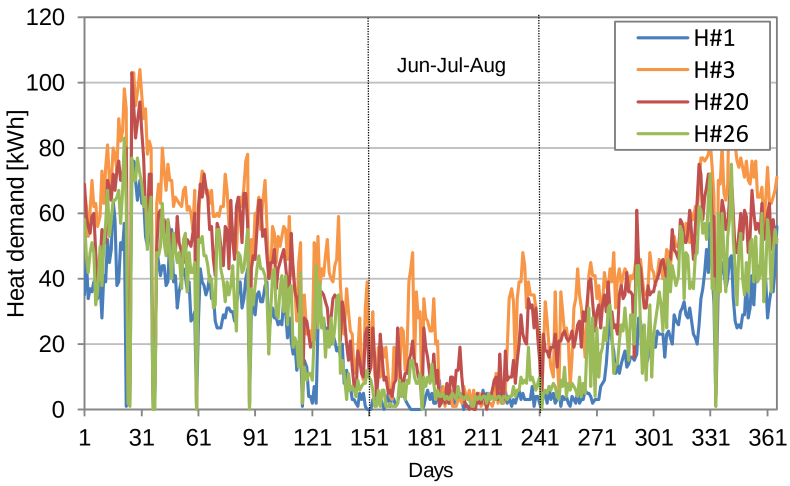


Figure 12. Heat demand profiles for the four selected houses.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

6. Discussion

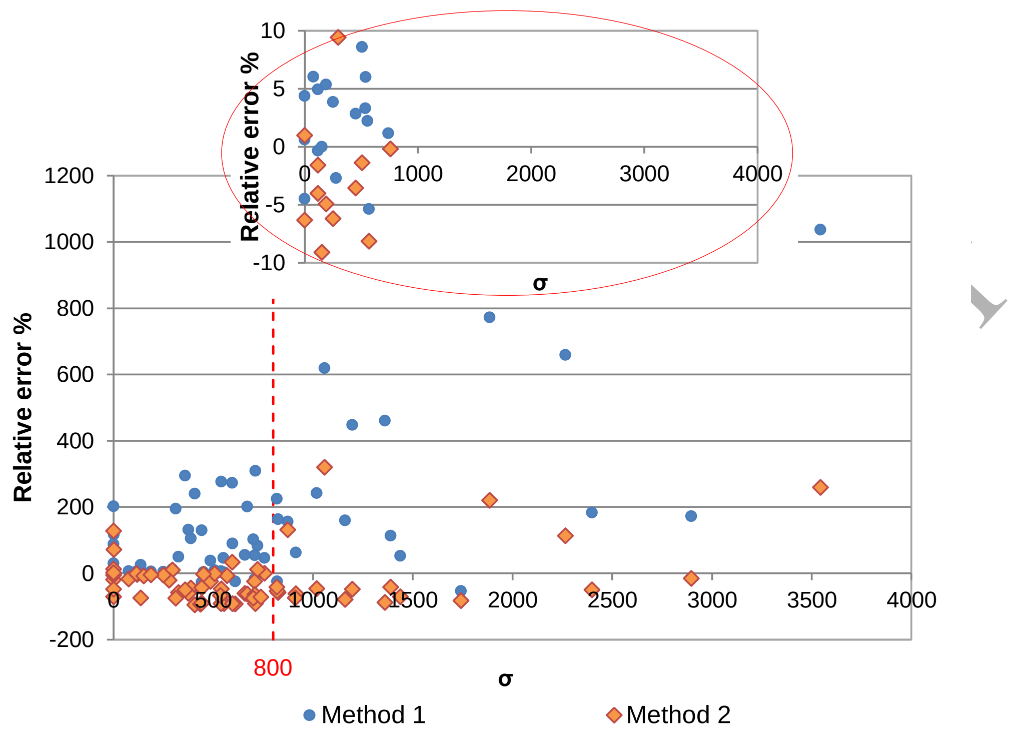
The validation results indicate that the accuracy of DHW usage prediction is strongly related to the ratio of DHW usage to the total heating demand, see Figure 5. Both methods could provide accurate prediction on mean hourly DHW usage when the ratio is above 0.5. The building and user typologies analysis shows that the methods are more reliable for application in newly built houses or apartments. Beside the DHW usage ratio, the space heating daily usage pattern also affects the accuracy of the DHW daily profile prediction. Large deviations appear in the cases in which the space heating usage varies during the day and overshadow the actual DHW usage leading to daily profiles without any pattern and/or with high base demand and no visible peaks that are typical for DHW usage profile, which is strongly correlated with the users' activity. Method 1 tends to overestimate the DHW consumption when the space heating usage has large fluctuations, while Method 2 has a risk of underestimating the DHW consumption when the space heating has higher demand during the night (0 am to 4 am) than the rest of the day.

When having only the hourly readings of total heat demand, the details on the DHW usage described above are unknown. Therefore, in order to be able to evaluate if the method can be applied, a preliminary data test should be done. A measure which captures the amount of variation of a data-set is the standard deviation - σ. The standard deviation is calculated using the raw hourly data on total heating demand during June-July-August (2208 hours). Figure 13 presents the relative error in relation to standard deviation, calculated using only summer data, since the annual data was not available for all the cases. In case of single-family houses, an increase in error with increasing standard deviation is clearer for Method 1 than for the Method 2. The apartments do not show this pattern.

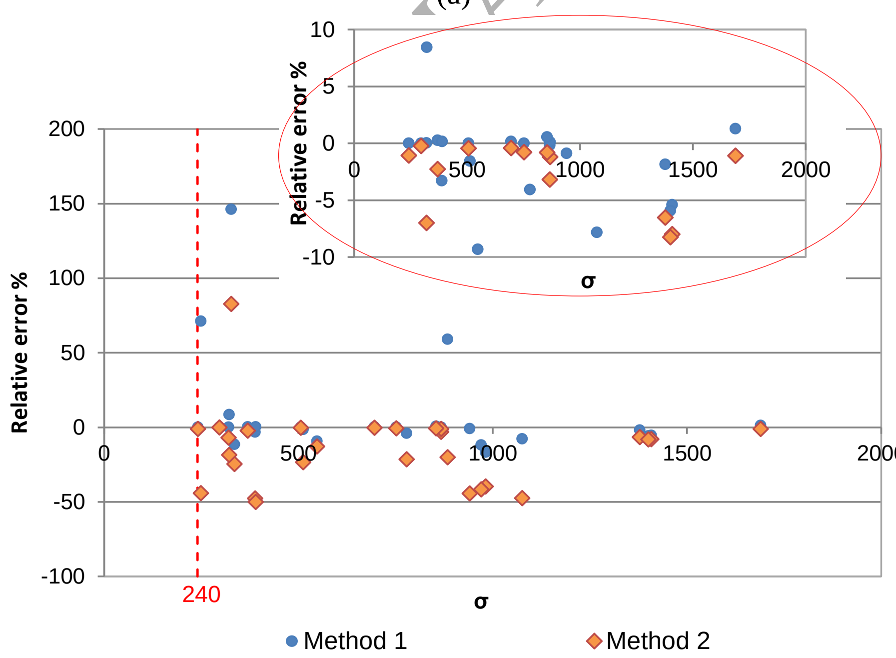
As mentioned in Section 4.1, a reasonable consistency between output and the input hourly profiles is with the relative error of ±10% [25]. Therefore, when focusing only on the results of relative error range between ±10%, it can be noticed that for the single-family houses the σ must be lower than 800 in order to achieve sufficient results. For the apartments, the requirement is reverse, i.e. there is only a lower limit to the σ, above which the results are good and it is equal to 240. However, when looking on all the results depicted in Figure 13, there are still cases when the relative error is above/below the limits of ±10% for the σ < 800 and σ > 240, and a statement claiming the methods always work with an σ above/below the given limits would be misleading. Table 2 presents the efficiency of the methods separately for single-family houses, apartments and for the whole data-set. The efficiency is calculated as the ratio of number of cases with relative error between ±10% to all cases with σ < 800 (single family-houses) and σ > 240 (apartments). Based on the numbers, it can be concluded that Method 2 and the assumptions behind it are not fully working and this method should be excluded from future work. Method 1 gives much better results, though primarly for the apartments, and the efficiency of almost 80% is found to be satisfying. On the other hand, the efficiency of 36% for single-family houses is found to be insufficient to recommend Method 2 for calculating the hourly DHW usage in single-family houses. There are a few reasons for these results: a) too little sample of houses, b) too general assumptions about the space heating usage during the summer, c) more complex DHW related user behaviour in the single-family houses compared to in the apartments, such like presents of more tapping places, i.e. guest toilet and/or utility room, which do not have well documented use, and d) not accounting for the assumptions in the holiday period, which is often the time when occupants are not at home and thus the DHW should be zero.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT



(a)



(b)

Figure 13. The relative error as a function of standard deviation. (a) Single family houses; (b) Apartments

Table 2 Efficiency of the methods for the relative error with the range of ± 10%

	Method 1	Method 2
Single-family houses (σ < 800)	36%	25%
Apartments (σ > 240)	79%	50%
All households	52%	34%

Furthermore, in the literature review by Fuentes et al. [3], the authors have presented international studies, which indicate that the DHW consumption is related to the outdoor temperature, i.e. with the increase of the external temperature the linear trend of energy usage decreases. The authors have given four reasons for this trend: a) the mains temperature is higher in warmer periods than during other seasons, b) smaller energy losses due to higher external temperature and c) the seasonal variations of the cold water temperature [31] d) occupants' behaviour, i.e. lower temperature during showers (less hot water) since the users do not need to warm themselves as compared to colder periods. Another reason of this trend could be the fact that summertime is the period of holidays, i.e. the occupants often travel and hence do not use the hot water at their houses. Taking into consideration the seasonal pattern of DHW usage, it can be discussed if the proposed methods give the average annual hourly consumption or only the summer average. Unfortunately, the studies of seasonal variations of DHW usage do not yet exist in Denmark and before drawing such conclusions more investigations must be done.

7. Conclusion

This paper presents a first attempt to develop a method enabling calculation of the mean hourly and the daily profile of DHW demand using hourly data on the total heating usage of a household. The method is validated with data from single-family houses and apartments and then applied to dataset consisting of hourly total heat consumption readings from 38 single-family houses delivered by the district heating company.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

The validation results indicated that the proposed methodology in some cases works very well, and in other cases the calculation results are far from the measured values, cf. Figure 7. Both Method 1 and Method 2 give satisfying results when the DHW usage during summer is at least at the same level as the space heating demand, cf. Figure 5. This is often the case in apartments and the energy-efficient houses, where the space heating demand is low, e.g. around 14 kWh/m^2 per year in passive houses, and hence the DHW usage constitutes a bigger share of the total heat demand. Yet, the ratio of DHW and space heating is unknown before applying the method. Therefore, currently the main challenge is to determine the cases for which the method will give satisfying results, i.e. relative error of ±10%.

The standard deviation was used as preliminary classification criterion for deciding if the method can or cannot be applied. Two limits were found σ >240 for apartments and σ < 800 for single-family houses. For the apartments the efficiency of the Method 1 is 79%, whereas for the single-family houses it is 36%. The Method 2 has efficiency of 50% and 25%, for apartments and single family houses respectively.

For the current stage, the standard deviation is a fine parameter to decide on the application of the method. The future development and the improvement of the method will proceed in two directions: a) analyzing the high resolution data and thus gaining better understanding of the users' practice related to domestic hot water and space heating consumption, e.g. if seasonal variation of DHW exists, and if so what are the reasons behind it, do the users turn off the floor heating during summer, where do they use most of DHW, what is the actual temperature of DHW, and b) clearly identifying for which household topologies the method works well.

Acknowledgements

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

The work presented in this paper was developed within the research project “User Practices, Technologies and Residential Energy Consumption – UserTEC” (0603-00586B INNOFOND_SP) financed by the Innovation Fund Denmark (IFD)

References

[1] European Comission - heating and cooling, (n.d.). https://ec.europa.eu/energy/en/topics/energy-efficiency/heating-and-cooling (accessed July 6, 2018).
[2] B. Bøhm, F. Schrøder, N.C. Bergsøe, SBi:2009:10 Varmt Brugsvand - Måling af forbrug og varmetab fra cirkulationsledninger [Domestic hot water - Measuring consumption and heat loss from circulation pipelines], 2009.
[3] E. Fuentes, L. Arce, J. Salom, A review of domestic hot water consumption profiles for application in systems and buildings energy performance analysis, Renew. Sustain. Energy Rev. 81 (2018) 1530–1547. doi:10.1016/j.rser.2017.05.229.
[4] H. Erhorn, H.E. Klutting, Selected examples of Nearly Zero- Energy Buildings, 2014.
[5] R. Yao, K. Steemers, A method of formulating energy load profile for domestic buildings in the UK, Energy Build. 37 (2005) 663–671. doi:10.1016/j.enbuild.2004.09.007.
[6] J. Frijns, J. Hofman, M. Nederlof, The potential of (waste)water as energy carrier, Energy Convers. Manag. 65 (2013) 357–363. doi:10.1016/j.enconman.2012.08.023.
[7] A. McNabola, K. Shields, Efficient drain water heat recovery in horizontal domestic shower drains, Energy Build. 59 (2013) 44–49. doi:10.1016/j.enbuild.2012.12.026.
[8] M.C. Rodríguez-Hidalgo, P.A. Rodríguez-Aumente, A. Lecuona, M. Legrand, R. Ventas, Domestic hot water consumption vs. solar thermal energy storage: The optimum size of the storage tank, Appl. Energy. 97 (2012) 897–906. doi:10.1016/j.apenergy.2011.12.088.
[9] E. Ampatzi, I. Knight, Modelling the effect of realistic domestic energy demand profiles and internal gains on the predicted performance of solar thermal systems, Energy Build. 55 (2012) 285–298. doi:10.1016/j.enbuild.2012.08.031.
[10] I. Knight, N. Kreutzer, M. Manning, M. Swinton, H. Ribberink, European and Canadian non-HVAC electric and DHW load profiles for use in simulating the performance of residential cogeneration systems, 2007.
[11] K. Gram-Hanssen, T. Christensen, L. Madsen, C. do Carmo, Sequence of practices in personal and societal rhythms – showering as a case., Time Soc. in press (2018).
[12] K. Ahmed, P. Pylsy, J. Kurnitski, Monthly domestic hot water profiles for energy calculation in Finnish apartment buildings, Energy Build. 97 (2015) 77–85. doi:10.1016/j.enbuild.2015.03.051.
[13] A. Ileri, S. Moshiri, Effects of common fuel and heating system options on the energy usage, pollutant emissions and economy, Energy Build. 24 (1996) 11–18. doi:10.1016/0378-7788(95)00960-4.
[14] M. Perlman, N. Milligan, Hot Water and Energy Use in Apartment Buildings, in: Symp. ASHRAE Trans., Dallas, TX, 1988: pp. 1087 – 1098.
[15] D. Colliver, W. Murphy, J. Taraba, Residential Water Heater Electrical Usage and Demand Reduction Using Reduced Element Sizes and Time Clock Controls, in: Symp. ASHRAE Trans., Dallas, TX, 1988: pp. 1110 – 1122.
[16] F. Goldner, DHW System Sizing Criteria for Multifamily Buildings, in: Symp. ASHRAE Trans, 1994.
[17] M. Aydinalp, V.I. Ugursal, A.S. Fung, Modeling of the space and domestic hot-water heating energy-consumption in the residential sector using neural networks, Appl. Energy. 79 (2004) 159–178. doi:10.1016/j.apenergy.2003.12.006.

ACCEPTED MANUSCRIPT

[18] D.S. Parker, Research highlights from a large scale residential monitoring study in a hot climate, Energy Build. 35 (2003) 863–876. doi:10.1016/S0378-7788(02)00244-X.
[19] Euroheat & Power, (n.d.). https://www.euroheat.org/news/district-energy-in-the-news/top-district-heating-countries-euroheat-power-2015-survey-analysis/ (accessed July 6, 2018).
[20] J. Wollerstrand, District Heating Substations. Performance, Operation and Design, Lund University, 1997.
[21] K. Winqvist, ed., How Europeans spend their time Everyday life of women and men, Office for Official Publications of the European Communities, Luxembourg, 2004.
[22] J. Bonke, Søvn – ægteskab, indkomst og helbred, GYLDENDAL, 2011.
[23] StyrdinVarmePumpe, (n.d.). https://www.styrdinvarmepumpe.dk/.
[24] T. Larsen, R. Jensen, O. Daniels, The comfort houses - Measurements and analysis of the indoor environment and energy consumption in 8 passive houses 2008-2011: Report No. 145, Aalborg, Denmark, 2012.
[25] V. Bakker, A. Molderink, J.L. Hurink, G.J.M. Smit, Domestic heat demand prediction using neural networks, in: Proc. 19th Int. Conf. Syst. Eng. ICSEng 2008, 2008: pp. 189–194. doi:10.1109/ICSEng.2008.51.
[26] S. Wei, R. Jones, P. De Wilde, Driving factors for occupant-controlled space heating in residential buildings, Energy Build. 70 (2014) 36–44. doi:10.1016/j.enbuild.2013.11.001.
[27] TABULA: National Building Typologies, (2018) 4–5.
[28] L.V. Madsen, Materialities shape practices and notions of comfort in everyday life, Build. Res. Inf. 46 (2018) 71–82. doi:10.1080/09613218.2017.1326230.
[29] A.R. Hansen, K. Gram-Hanssen, H.N. Knudsen, How building design and technologies influence heat-related habits, Build. Res. Inf. 46 (2018) 83–98. doi:10.1080/09613218.2017.1335477.
[30] K. Nærvig-Petersen, K. Gram-Hanssen, SBi2005:09 Husholdningers energi- og vandforbrug, 2005.
[31] K. Gerin, O.; Bleys, B.; De Cuyper, Seasonal variation of hot and cold water consumption in apartment buildings, CIBW06 Symp. (2014) 1–9. https://www.wtcb.be/homepage/download.cfm?dtype=research&doc=A2_1523.pdf&lang=en.

ACCEPTED MANUSCRIPT